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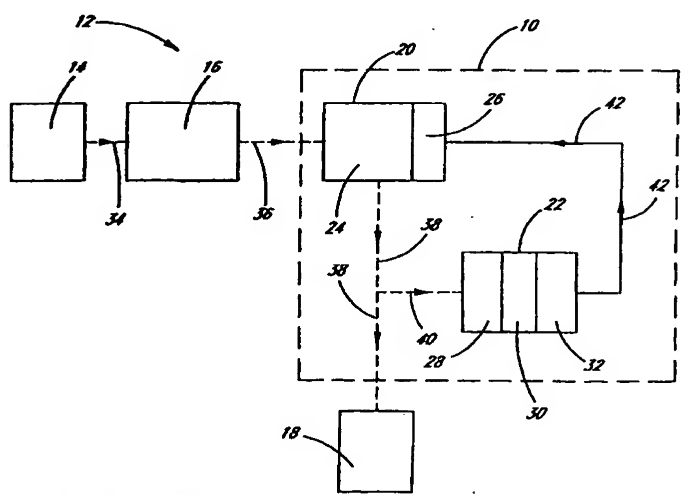
(54) Title: TAPPED DELAY LINE DIFFRACTIVE ARRAY FOR SENSING POLARIZATION MODE DISPERSION




(57) Abstract: An apparatus and method for compensating for polarization mode dispersion (PMD) of an optical signal propagating in an optical fiber involves optical processing the signal to quantify the amount of PMD. A spectrum analyzer (28, 68), which preferably comprises a tapped delay line diffractive array, is employed to produce a diffraction pattern that is sampled to retrieve data about the optical power spectrum of the signal. A figure of merit based on the optical power spectrum is then used to control a polarization mode dispersion compensator (20, 24). This figure of merit may be based on the autocorrelation function of the optical signal or from the flatness of the intensity across the diffraction pattern. Signal processing of the diffraction pattern yields a value for the figure of merit that can be used to impart delay in the fast component of the optical signal with the polarization mode dispersion compensator (20, 24).

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# TAPPED DELAY LINE DIFFRACTIVE ARRAY FOR SENSING POLARIZATION MODE DISPERSION

## Background of the Invention

### 1. Field of the Invention

The present invention relates generally to signal transmission in an optical fiber, and more specifically to compensating for polarization mode dispersion (PMD) of an optical signal propagating in an optical fiber.

### 2. Technical Background

An optical signal propagating within a fiber can be considered to a first order approximation as comprising two polarizations corresponding to two eigenpolarizations of the fiber. The optical signal experiences polarization mode dispersion (PMD) due to different amounts of time delay for the two polarizations resulting from birefringence in the optical fiber. Environmental factors, such as temperature and pressure, cause the two eigenpolarizations of an optical fiber and the resultant propagation delay between them to change over time.

PMD is a significant problem for high data-rate fiber optic communications where data is transmitted at about 10 gigabits per second (Gbits/sec). Digital data in the form of optical pulses (100 picoseconds wide for data transmitted at 10 Gbits/sec) is sent over optical fiber and detected by an optical detector. The optical detector that receives an optical pulse cannot distinguish between the two polarizations modes but instead detects a single pulse that is broadened as a result of the delay between the two

polarization modes. The difference in delay can be on the order of 10 to 20 picoseconds (ps) for a 100 kilometer (km) fiber, which results in significant broadening when the optical signal comprises optical pulses 100 ps in width. This broadening of the pulses in a digital signal; herein referred to as filtering, is sufficient to cause intersymbol interference and drastically increases the probability of bit errors.

Conventional optical communication systems that reduce signal degradation caused by PMD direct the optical pulses comprising the optical signal to the detector and then analyze electrical pulses produced by the optical detector for an indication of the presence of filtering. Electrical feedback from the optical detector is employed to adjust parameters in the optical communications system until the electrical signal is least distorted.

## Summary of the Invention

An apparatus for compensating for polarization mode dispersion of an optical signal propagating in an optical fiber comprises compensator optics and an optical signal sensor. The compensator optics has an input which receives the optical signal and an output which outputts the optical signal. The optical signal sensor receives a portion of the signal output from the compensator optics, analyzes the polarization mode dispersion of the optical signal, and provides a compensation signal to the compensation optics indicative of the amount of polarization mode dispersion. The compensator optics responsively alters the optical signal to compensate for the polarization mode dispersion. The optical signal sensor comprises an optical processor which generates a spatial pattern and a detector situated so as to measure intensity at a plurality of locations across the spatial pattern. The sensor generates the compensation signal in response to the measured intensity.

Another aspect of the invention comprises a method of producing a compensation signal for driving compensator optics in a polarization mode dispersion compensation apparatus. The method includes optically processing an output of the compensator optics to produce an optically processed signal having a spatial distribution. The processed signal is directed onto a detector and the intensity is

measured at a plurality of locations across the spatial distribution to thereby produce an intermediate signal. The intermediate signal is processed to generate the compensation signal.

A separate aspect of the invention comprises an apparatus for compensating for polarization mode dispersion of a first optical signal corresponding to a train of optical digital data pulses propagating at a bit rate, *R*, in an optical fiber. This apparatus includes compensator optics and an optical signal sensor. The compensator optics has an input which receives the first optical signal and an output which outputs the first optical signal. The optical signal sensor receives a portion of the signal output from the compensator optics, analyzes the polarization mode dispersion of the optical signal, and provides a compensation signal to the compensation optics indicative of the amount of polarization mode dispersion. The compensator optics responsively alters the first optical signal to compensate for the polarization mode dispersion. The optical signal sensor comprises an optical processor which generates a second optical signal comprising a signal other than a train of optical digital data pulses propagating at a bit rate *R*. The sensor generates the compensation signal in response to the second optical signal.

A separate aspect of the invention comprising an apparatus for compensating for polarization mode dispersion of an optical signal propagating in an optical fiber includes compensator optics and an optical signal sensor. The compensator optics has an input which receives the optical signal and an output which outputs the optical signal. The optical signal sensor receives a portion of the signal output from the compensator optics, analyzes the polarization mode dispersion of the optical signal, and provides a compensation signal to the compensation optics indicative of the amount of polarization mode dispersion. The compensator optics responsively alters the optical signal to compensate for the polarization mode dispersion. The optical signal sensor comprises an optical processor which has a transfer function and which generates a spatial pattern corresponding to the convolution of the spectral distribution of the signal output from the compensator optics with the transfer function. The sensor generates the compensation signal in response to the spatial pattern.

Another aspect of the invention comprises a method of producing a compensation signal for driving compensator optics in a polarization mode dispersion compensation apparatus. The method includes optically processing an output of the compensator optics to produce an optically processed signal using an optical device having a transfer function to produce a spatial distribution which corresponds to the convolution of the spectrum of the output of the compensator optics with the transfer function. The processed signal is directed onto a detector to provide a detected signal. The detected signal is processed to generate the compensation signal.

A separate aspect of the invention comprises an apparatus for compensating for polarization mode dispersion of a first optical signal comprising optical pulses propagating in an optical fiber. This apparatus includes compensator optics and an optical signal sensor. The compensator optics has an input which receives the first optical signal and an output which outputs the first optical signal. The optical signal sensor receives a portion of the signal output from the compensator optics, analyzes the polarization mode dispersion of the optical signal, and provides a compensation signal to the compensation optics indicative of the amount of polarization mode dispersion. The compensator optics responsively alters the first optical signal to compensate for the polarization mode dispersion. The optical signal sensor comprises an optical processor which generates a second signal and an optical detector having an integration time that is substantially longer than the time between adjacent optical pulses in the first optical signal. The detector receives the second optical signal and generates an electrical signal. The sensor generates the compensation signal in response to the electrical signal.

Another aspect of the invention comprising an apparatus for compensating for polarization mode dispersion of an optical signal propagating in an optical fiber includes compensator optics and an optical signal sensor. The compensator optics has an input which receives the optical signal and an output which outputs the optical signal. The optical signal sensor receives a portion of the signal output from the compensator optics, analyzes the polarization mode dispersion of the optical signal, and provides a compensation signal to the compensation optics indicative of the amount of

polarization mode dispersion. The compensator optics responsively alters the optical signal to compensate for the polarization mode dispersion. The optical signal sensor comprises an optical processor which includes a beamsplitter that splits the optical signal into a plurality of signals and a region where the plurality of signals optically interfere with each other to form another optical signal. The sensor generates the compensation signal in response to the another optical signal.

A separate aspect of the invention also comprises a method of producing a compensation signal for driving compensator optics in a polarization mode dispersion compensation apparatus. This method includes processing an output of the compensator optics to produce a processed signal, the processing comprising autocorrelating the processed signal at a time $t_1$ and a time $t_2$. The autocorrelation at time $t_1$ is compared with the autocorrelation at time $t_2$, and the compensation signal is produced in response to the comparing.

Another aspect of the invention comprises a method of controlling compensator optics in a polarization mode dispersion compensation apparatus comprising a polarization transformer and delay optics. The method includes processing an input signal comprised of an output of the compensator optics. The processing provides an optimization parameter which is measured. Control signals are produced for controlling both the polarization transformer and the delay optics in response to measurements of the same optimization parameter.

An additional aspect of the invention includes an apparatus comprising compensator optics and an optical signal sensor, the compensator optics comprising a polarization transformer and delay optics. The compensator optics has an input for receiving light from an optical fiber which propagates light in first and second polarizations. The polarization transformer receives light from the optical fiber. The delay optics receives light from the polarization transformer and propagates light in third and fourth polarizations. The optical signal sensor receives light from the compensator optics. The optical signal sensor comprises an optical element having first and second states, one of the states passing light of the third polarization while blocking light of the fourth polarization, and the other of the states passing at least a portion of

light of both the third and fourth polarizations. The sensor produces control signals for the polarization transformer when the optical element is in the first state and produces control signals for the delay optics when the optical element is in the second state.

Another aspect of the invention comprises an apparatus comprising a polarization transformer, delay optics, and sensor optics. The delay optics comprise a polarizing beamsplitter for splitting a beam into first and second beams of different polarizations and a mirror positioned to receive the first beam and reflect the first beam back to the polarizing beamsplitter. The delay optics additionally comprise a mirror positioned to receive the second beam and reflect the second beam back to the polarizing beamsplitter, a first quarter-wave plate positioned in the path of the first beam, and a second quarter-wave plate positioned in the path of the second beam. The polarizing beamsplitter combines the reflected first and second beams to provide an output beam.

## Brief Description of the Drawings

Figure 1 is a block diagram of a preferred embodiment of the present invention;

Figure 2 is a schematic representation of a preferred embodiment of the present invention.

Figure 3A is a plot, on axes of time (in arbitrary units) and magnitude (in arbitrary units), that shows baseband autocorrelation functions for consecutive measurements of an optical signal output from a preferred embodiment of the present invention;

Figure 3B is a plot, on axes of time (in arbitrary units) and magnitude (in arbitrary units), depicting ratios of the baseband autocorrelation functions shown in Figure 3A;

Figure 4 is a plot, on axes of spatial location (in arbitrary units) and intensity (in arbitrary units), which depicts a near field image of a tapped delay line diffractive array employed in a preferred embodiment of the present invention;

Figure 5 is a plot, on axes of spatial location (in pixels) and intensity (in arbitrary units), which depicts diffraction patterns in the far field (i.e., in the Fraunhofer

region) created by monochromatic light emanating from the tapped delay line diffractive array. Two diffraction patterns corresponding to two different wavelengths of light are shown;

Figure 6 is a plot, on axes of spatial location (in arbitrary units) and intensity (in arbitrary units), which depicts diffraction patterns in the Fraunhofer region created by monochromatic light emanating from the tapped delay line diffractive array. Nine diffraction patterns corresponding to nine different wavelengths of light are shown; and

Figure 7 is a plot, on axes of spatial location (in arbitrary units) and intensity (in arbitrary units), depicting diffraction patterns in the Fraunhofer region created by monochromatic light emanating from the tapped delay line diffractive array that shows the effect of modulation and PMD on the diffraction pattern.

## Detailed Description of the Preferred Embodiments

A block diagram of an apparatus 10 for compensating for polarization mode dispersion of an optical signal propagating in an optical fiber, in accordance with a preferred embodiment of the present invention, is shown in FIGURE 1. This apparatus 10 is incorporated in an optical communications system 12 comprising an optical transmitter 14, an optical fiber 16, and an optical receiver 18. The apparatus 10 for compensating for polarization mode dispersion of an optical signal propagating in an optical fiber is located between the optical fiber 16 and the optical receiver 18. As depicted in FIGURE 1, the apparatus 10 comprises a compensator 20 and an optical signal sensor 22. The compensator 20, includes compensator optics 24 and an electronic controller 26 electrically connected thereto, while the optical signal sensor 22 includes an optical processor 28, an optical detector 30, and an electronic processor 32 electrically connected thereto. The electronics processor 32 in the optical signal sensor 22 and the electronics controller 26 in the compensator 20 are also electrically connected.

A signal (represented by a dashed line 34) originating from the optical transmitter 14 is transmitted through the optical fiber 16, which disadvantageously introduces a temporal delay in one of the polarization modes. An uncompensated

optical signal (represented by a dashed line 36) that is output from the optical fiber 16 is passed through the apparatus 10 to compensate for polarization mode dispersion and is outputted as a compensated optical signal (indicated by a dashed line 38) that is sent to the optical receiver 18. The compensator 20, and more specifically, the compensator optics 24, receive the uncompensated optical signal sent through the optical fiber 16 and produces the compensated optical signal as output. A portion of this compensated optical signal (signified by a dashed line 40) is directed to the optical signal sensor 22, which analyzes the polarization mode dispersion in the compensated optical signal. The optical signal sensor 22 in turn provides an electrical compensation signal (denoted by arrows 42) to the compensator 20, and more specifically, to the electronic controller 26 indicative of the amount of polarization mode dispersion. The electronic controller 26 adjusts the compensation optics 24 so as to responsively alter the uncompensated optical signal to properly compensate for the polarization mode dispersion.

As shown in FIGURE 2, the compensator optics 24 in the apparatus 10 for compensating for polarization mode dispersion comprises a polarization transformer 44 and delay optics 46. The polarization transformer 44 includes a half-wave plate 48 juxtaposed with a quarter-wave plate 50 having respective optic axes as is well known in the art. The half-wave plate 48 and the quarter-wave plate 50 are mounted on an electrically controlled rotation stages 52 that are electrically connected to the electronic controller 26 of the compensator 20. These rotation stages 52 permit the half-wave plate 48 and the quarter-wave plate 50 to be independently rotated. The delay optics 46 comprise a polarization beamsplitter 54 and two arms, a first 56 and a second 58, extending from two sides of the beamsplitter, each arm comprising a quarter-wave plate 60 and a mirror 62. The mirror 62 in the second arm 58 is mounted on an electrically controlled translation stage 64 that is electrically connected to the electronic controller 26 for the compensator 20.

As discussed above, the optical signal sensor 22 in the apparatus 10 for compensating for polarization mode dispersion comprises the optical processor 28, the optical detector 30, and the electronic processor 32; the optical processor comprising a polarization analyzer 66 and a tapped delay line diffractive array 68, the optical detector

comprising an linear detector array, and the electronic processor comprising Fourier transform and other signal processing electronics. The polarization analyzer 66 in the optical processor 28, or analyzer as it is know in the art, comprises liquid crystal 70 adjacent a polarizer 72. Alternatively, the analyzer may comprise a polarizer mounted on a rotation stage as is well known in the art. The tapped delay line diffractive array or delay line optical spectrum analyzer 68 comprises a structure having an array of outputs that provides time-delayed versions of a signal input into the structure, the time delay being proportional to the position along the array. In particular, the delay line optical spectrum analyzer 68 preferably comprises a fiber optic coupler having a single fiber input 74 and a plurality of output fiber lines 76; the output fiber lines are cut at one end 78 so as to have increasing path lengths and the ends of the output fiber lines are arranged in a line to form a linear array 80. Eight such output lines 76 are shown in FIGURE 2, the second output line being about one centimeter longer than the first output line, the third being about one centimeter longer than the second, the fourth, about one centimeter longer than the third, etc. Accordingly, the eighth output line is about one centimeter longer than the seventh output line and about seven centimeters longer than the first. The linear detector array comprises InGaAsP, which is sensitive to light having a wavelength of 1550 nm, the wavelength of the optical signal. This linear detector array has a plurality of pixels 82 spaced apart by about 50 micrometers (μm) and located a distance *d* that is approximately five inches (in.) from the delay line optical spectrum analyzer 68. A beamsplitter 84 and coupling lens 86 are juxtaposed with the optical processor 28 in the optical signal sensor 22.

As shown in FIGURE 2, the apparatus 10 for compensating for PMD may include bulk optics, fiber optics, or waveguide optics or a combination thereof. For example, while the delay optics 46 in FIGURE 2 comprise bulk optics, the tapped delay line diffractive array 68 is a fiber optic device. Alternatively, the apparatus 10 may be implemented using entirely bulk optics, fiber optics, or waveguide optics, or may comprise some components that are waveguide, fiber optic, or bulk optic devices.

The optical communication system 12 operates in a conventional manner with the exception of the apparatus 10 for compensating for PMD inserted therein. The

optical transmitter 14 sends a modulated optical signal, i.e., a series of pulses, corresponding to digital data over the optical fiber 16, which disadvantageously introduces polarization mode dispersion into the modulated optical signal. As described above, the optical signal propagating within the optical fiber 16 can be considered to a first order approximation as comprising two polarization modes or components corresponding to two eigenpolarizations of the fiber. As a result of birefringence in the optical fiber 16, one of these polarization components, herein referred to as the slow component, is delayed with respect to the other polarization component, the fast component. In accordance with the present invention, the modulated optical signal exiting the optical fiber 16 is directed into the apparatus 10 for compensating for polarization mode dispersion, which to a first order, introduces delay into the faster component until no differential delay know as differential group delay exists between the two polarization modes.

More specifically, the optical signal from the optical fiber 16 is passed through the polarization transformer 44 that transforms the optical signal, which is generally elliptically polarized, into linearly polarized light. Furthermore, this linearly polarized light is "rotated" such that the electric field is oriented in a specific direction. Polarization transformers 44 that convert elliptically polarized light propagating in a direction $\hat{z}$ into linearly polarized light having an electric field oriented at a specific angle $\theta$ with respect a fixed direction $\hat{x}$ (or $\hat{y}$) perpendicular to the propagation direction $\hat{z}$ are well known in the art. This transformation is preferably accomplished by passing the elliptically polarized light exiting the optical fiber 16 through the half-wave plate 48 and the quarter-wave plate 50 in the compensator optics 24 while the half-wave plate and the quarter-wave plate are each rotated about an axis, herein referred to as the optical axis, which is parallel to the propagation direction $\hat{z}$. Using the respective rotation stages 52, the half-wave plate 48 and the quarter-wave plate 50 are independently rotated about the optical axis until linearly polarized light oriented at a specific angle $\theta$ is obtained. Although the polarization transformer 44 may comprise a half-wave plate and a quarter-wave plate, a liquid crystal cell may alternatively be employed.

The optical signal after traveling through the polarization transformer 44 is directed into the polarizing beamsplitter 54 in the delay optics 46 where light having a first polarization is reflected into the first arm 56 of the delay optics while light of a second orthogonal polarization is transmitted through the beamsplitter into the second arm 58. The linearly polarized light exiting the polarizing beamsplitter 54 passes through the quarter-wave plates 60 in the first and second arms 56, 58, thereby transforming the linearly polarized light into circularly polarized light, which is reflected off the mirrors 62 in the two arms.. The beam of light in each arm 56, 58 travels a different distance from the beamsplitter 54 to the respective mirror 62 and back through the beamsplitter. In this manner, a time delay is introduced into one of the beams and, correspondingly, into one of the polarizations. The amount of time delay is adjusted by moving the mirror 62 in the second arm 58 closer or farther away from the beamsplitter 54 using the linear translation stage 64, thereby altering the distance that light having the second polarization must travel. The circularly polarized beams in both arms 56, 58, upon reflection from either mirror 62, once again pass through the quarter-wave plates 60 and are converted to linearly polarized light. However, the linearly polarized light exiting each arm 56, 58 is rotated 90° about the optical axis with respect to the linearly polarized light entering each arm as a result of the half wave of phase shift introduced by passing through the quarter-wave plates 60 twice. Consequently, the beam in the first arm 56, which was initially reflected from the polarizing beamsplitter 54, is transmitted through the beamsplitter while the beam in the second arm 58, which was initially transmitted through the polarizing beamsplitter, is reflected by the beamsplitter away from the first arm. Accordingly, the two beams, recombined, are directed away from the compensator optics 24 and to the optical receiver 18.

Compensation of the polarization mode dispersion is achieved by adjusting the polarization transformer 44, i.e., rotating the half-wave plate 48 and the quarter-wave plate 50, until the slow polarization component is directed into the first arm 56 having fixed optical length and the fast component is directed into the second arm 58 having variable optical path length. The optical path length of the second arm 58 is then

adjusted to impart a temporal delay on the fast polarization component so that the slow polarization component is not delayed with respect to the fast polarization component. Alternatively, the fast polarization can be sent to the first arm 56 and the slow polarization to the second 58, and the optical path in the second arm shortened to impart temporal delay in the fast component, which is in the first arm. Accordingly, when properly adjusted, the polarization transformer 44 converts generally elliptically polarized light into linearly polarized light that is the vector sum of two orthogonal components corresponding to the fast and slow eigenpolarization modes of the optical signal output by the optical fiber 16; these two orthogonal components match the first and second polarizations of the polarizing beamsplitter 54. The optical path length in the two arms 56, 58 of the delay optics 46 is then varied to match the delay in the two polarization components traveling therein.

The optical signal sensor 22 samples a portion of the signal output from the compensator 20 and provides feedback thereto that indicates when adjustments in the compensator, i.e., adjustments to the polarization transformer 44 and the delay optics 46, improve the PMD compensation. The beamsplitter 84, a partially reflecting mirror, and the coupling lens 86 direct a portion of the optical signal output from the compensator 20 to the optical processor 28 of the optical signal sensor 22. This optical signal is first sent through the polarization analyzer 66, which has two states: a first state that passes light in one of the arms 54, 56 of the delay optics 46 while blocking light in the other arm and a second state that passes some light from each of the arms, preferably in equal amounts. The polarization analyzer 66 is set in the first state to transmit only linearly polarized light having a polarization corresponding to the polarization of e.g., the first arm 54, (or alternatively of the second arm 56) while the polarization transformer 44 is adjusted. If the polarization transformer 44 is not properly set, then the light in the first arm 56 will include components from both the fast and the slow eigenpolarization modes and the relative temporal delay between the two modes will broaden the pulses in the optical signal. This broadening in the optical signal can thus be monitored by the optical signal sensor 22 to set the polarization transformer 44 such that the designated arm, e.g., the first arm 54, corresponds to the

fast eigenpolarization mode and the other arm, corresponds to the slow eigenpolarization mode. The polarization analyzer 66 is then set in the second state to transmit in equal amounts linearly polarized light having a polarization corresponding to the polarization of the first arm 54 and of the second arm 56 while adjusting the delay optics 46. If the delay optics 46 are not properly adjusted, then the light exiting the compensation optics 24 will not be fully compensated and a relative delay will remain between the two polarization modes thereby broadening the pulses in the optical signal.

The extent of broadening of the pulses in the optical signal can be determined by examining the optical power spectrum of the optical signal. An optical signal devoid of broadening will exhibit a clean full spectrum. According to the Wiener-Khinchin theorem, the cleanest, fullest spectrum corresponds to the narrowest optical autocorrelation function. Thus, a compensated optical signal not degraded by PMD will possess a narrow optical autocorrelation function and equivalently a minimum correlation time. When the narrowest optical autocorrelation function is obtained, PMD compensation will have been achieved.

To obtain the optical power spectrum and the optical autocorrelation function, the optical signal is passed through an optical spectrum analyzer, a device such as a grating, used for measuring the wavelength or optical frequency of light. In this embodiment, the tapped delay line diffractive array or delay line optical spectrum analyzer 68 is employed as the spectrum analyzer since the tapped delay line diffractive array enables narrow band spectral analysis of quasi-monochromatic optical signals. As used herein, narrow band means $f << c/\lambda$, where $f$ is the frequency bandwidth, which may for example, be in the range of about 10 gigahertz (GHz), $\lambda$ is the wavelength of the optical signal, $c$ is the speed of light in free space, and $c/\lambda$ is the carrier or center frequency, which is in the range of terahertz (THz). As shown in FIGURE 2, the optical signal transmitted through the polarization analyzer 66 enters the single input fiber line 74 of the tapped delay line diffractive array 68, which is split into N, here eight, fibers 76 having outputs arranged to form the linear array 80. Since the length of the eight output lines 76 increases incrementally from the first line to the eighth line,

the optical signal output from the output fiber lines experiences incremental time delay and corresponding phase delay. The tapped delay line diffractive array 68, thus, converts the input optical signal into an array of outputs representing time-delayed version of the input signal, the delay time being proportional to the position along the array. Advantageously, the phase difference between adjacent outputs varies linearly with frequency. As a consequence, the diffraction pattern resulting from the field emitted by this diffractive array 68 will exhibit frequency dependent regions of constructive interference similar to a diffraction grating. Similarly, the power spectrum can be estimated from the resulting diffraction pattern. The optical detector 30 is likewise placed a distance, *d*, from the tapped delay line diffractive array 68 in the Fraunhofer diffraction region to obtain an image of the far-field diffraction pattern from which the optical power spectrum can be extracted.

For a modulated optical signal, the diffraction pattern on a plane in the Fraunhofer region corresponds the baseband spectrum $S(x)$ of the modulating signal, i.e., the digital data, convolved with the transfer function $h(x)$ of the tapped delay line diffractive array. Here, $x$ corresponds to spatial position on the plane in the Fraunhofer region, or more specifically, on the optical detector 30. Frequency is converted into spatial position on the optical detector 30 via the angular dispersion introduced by the spectrum analyzer, which in this embodiment comprises the tapped delay line diffractive array 68. The angular dispersion is given by the formula $\Delta x = k\,\Delta\nu$, where $\Delta x$ is the shift in position on the optical detector 30 for a shift in optical frequency of $\Delta\nu$; $k$ is the dispersion coefficient that increases with delay between outputs from adjacent output lines in the taped delay line diffractive array. The optical detector 30 outputs an electrical signal that represents to the light intensity pattern on the detector array. This electrical signal it sent to the electronic processor 32 which performs the fast Fourier transform (FFT) on the signal. As is well known, the Fourier transform of the convolution of two functions is equal to the product of the Fourier transform of those functions. The Fourier transform of the transfer function $h(x)$ is defined herein as $H(u)$, where $u$ is the spatial frequency variable associated with the spatial variable $x$. Also, according to the Wiener-Khinchin theorem, the Fourier transform of the power

spectrum $S(x)$ is the autocorrelation function $\phi(u)$, and vice versa. Thus, the Fourier transform of the convolution of the transfer function $h(x)$ with the baseband spectrum $S(x)$, is equivalent to the product of the Fourier transform of the transfer function and the autocorrelation function; i.e., the Fourier transform of $S(x) * h(x)$ is $\phi(u)H(u)$.

To determine when adjustments in the compensator 20, i.e., adjustments to the polarization transformer 44 and the delay optics 46, improve the PMD compensation, a comparison is made between two optical autocorrelation functions for two separate readings, one before an adjustment is made in the compensator optics 24 and one after the adjustment is made. The pattern obtained at the optical detector 30 during the first reading is $S_1(x) * h(x)$ while the pattern obtained at the optical detector during the second reading is $S_2(x) * h(x)$. Accordingly, the Fourier transform of these patterns is $\phi_1(u)H(u)$ and $\phi_2(u)H(u)$, respectively. By taking the ratio of the Fourier transform of the patterns, i.e., of $\phi_1(u)H(u)$ and $\phi_2(u)H(u)$, the common $H(u)$ term cancels out and a ratio of the respective autocorrelation function $\phi_1(u)/\phi_2(u)$ is obtained. Likewise, an electrical signal based on the measured ratio is sent to the electronic controller 26 in the compensator 20, which controls the polarization transformer 44 or the translation stage 64 in the second arm 58 of the delay optics 46.

As discussed above, the optical signal will exhibit the cleanest, fullest optical power spectrum, and equivalently, the narrowest optical autocorrelation function, when not degraded by PMD. Two normalized baseband autocorrelation functions $\phi_1(u)$ and $\phi_2(u)$ for two consecutive measurements of an optical signal output are shown as two curves 88, 90 in FIGURE 3A. The autocorrelation function $\phi_2(u)$, curve 90, is narrower than $\phi_1(u)$, curve 88, and, thus, corresponds to the better compensated signal. FIGURE 3B depicts ratios $\phi_2(u)/\phi_1(u)$, curve 92, and $\phi_1(u)/\phi_2(u)$, curve 94, of the baseband autocorrelation functions shown in FIGURE 3A. If the narrower $\phi_2(u)$ 90 was measured after $\phi_1(u)$ 88, the conclusion is that the adjustment to the compensator optics has improved the PMD compensation. For such a case, the curve 92 corresponding to the ratio $\phi_2(u)/\phi_1(u)$ has a central peak. If, in contrast, $\phi_1(u)$ 88 was measured after $\phi_2(u)$ 90, i.e., the case where adjustment to the compensator worsens the PMD compensation,

the ratio $\phi_1(u)/\phi_2(u)$, curve 94, has no central peak. Accordingly, the center of the curves 92, 94 corresponding to the ratio of the optical autocorrelation functions may be employed as a figure of merit to determine whether a given adjustment to the compensator 20 improves or worsens the compensation. A higher value of this figure of merit would indicate improvement. Alternatively, the value obtained by integrating over the entire curve 92, 94 may be used as the figure of merit, in which case, a lower value signifies improvement. By monitoring the changes in the value of the figure of merit when the compensator 20 is adjusted different amounts, the settings for the compensator that maximize the compensation can be realized. When the value for the figure of merit no longer changes with adjustments to the compensator 20, or if the figure of merit oscillates in value for small adjustments because of noise in the system, the compensator cannot be optimized further.

In each case, the figure of merit is fundamentally based on the optical spectrum of the optical signal output from the compensator 20, a spatial pattern containing information about the optical spectrum being displayed on the optical detector 30. The tapped delay line diffractive array 68 or delay line optical spectrum analyzer provides the optical power spectrum over a narrow band. In the embodiment depicted in FIGURE 2, the bandwidth is about 10 GHz. The output fiber lines 76 are cut such that adjacent fibers differ in length by about 1 centimeter (cm), which corresponds to a relative delay, T, of about 50 picoseconds (psec) between two optical signals in two adjacent output fiber lines. This delay between adjacent outputs determines the sampling interval for the diffractive array 68. The inverse of the sampling interval (i.e., 1/T) establishes the free spectral range provided by the array 68. In this embodiment, the free spectral range is about 20 GHz. To satisfy the Nyquist sampling theorem and to avoid aliasing, the optical bandwidth of the signal should be less than half the free spectral range; thus, the bandwidth of the optical signal should be less than about 10 GHz. The spectral resolution provided by the array equals the free spectral range divided by the number of taps or output fiber lines 76 into which the optical signal is coupled. Since the diffractive array 76 produces eight time-delayed outputs, the spectral resolution obtained is about 2.5 GHz.

FIGURE 4 shows a near field image of the output of the tapped delay line diffractive array 68 produced by imaging the array using a lens. This lens is not included in the apparatus 10 of FIGURE 2 as the optical detector 30 is situated so as to obtain the far field diffraction pattern. FIGURE 5 depicts experimentally obtained diffraction patterns created by unmodulated monochromatic light emanating from the tapped delay line diffractive array 68 and detected by the optical detector 30 located in the far field (i.e., in the Fraunhofer region). The pixels 82 in the optical detector 30 are spaced at 50 μm intervals, and the detector array is place five inches from the tapped delay line diffractive array 68. The diffraction patterns shown in FIGURE 5 extend across 32 of the pixels 82. The far field, i.e. Fraunhofer, diffraction pattern associated with this diffractive array 68 yields a fixed pattern for a given wavelength. For small variations in wavelength, this pattern remains similar in shape, except for an overall shift in angle that is proportional to wavelength shift. Two diffraction patterns 96, 98 corresponding to two different wavelengths of light, 1550.00 and 1550.01 nanometers, respectively, are shown in FIGURE 5. The two detected diffraction patterns 96, 98 are separated in wavelength by 0.01 nm, which corresponds a spectral frequency of 1.25 GHz. As expected, except for small variations, the pattern retains its shape but shifts one pixel 82 or about 50 microns in a plane about five inches from the diffractive array 68. Accordingly, the angular dispersion of the array can be determined to be about 1.1 arc minute/GHz. This shift in one pixel 82 caused by the 0.01 nm difference in wavelength, or 1.25 GHz difference in frequency, equals about half the period of the fastest spatial variation in the detected patterns 96, 98. Thus, the fastest spatial variation detected can be estimated from the diffraction patterns 96, 98 to be about 2.5 GHz. This value for spectral resolution corresponds to the value of 2.5 GHz calculated above for a tapped delay line diffractive array 68 having eight taps with delay between adjacent outputs of about 50 psec.

FIGURE 6 depicts nine experimentally obtained diffraction patterns 100 created by unmodulated light emanating from the tapped delay line diffractive array 68 and detected by the optical detector 30 while located in the Fraunhofer region. The nine diffraction patterns 100 correspond to nine different wavelengths of light: 1550.00,

1550.01, 1550.02, 1550.03, 1550.04, 1550.05, 1550.06, 1550.07, and 1550.08 nanometers. Consecutive diffraction patterns are separated in wavelength by 0.01 nm, which corresponds a spectral frequency of 1.25 GHz. Thus, the nine diffraction patterns 100 span a total of 10 GHz, the bandwidth established by the Nyquist sampling theorem.

FIGURE 7 depicts numerically calculated diffraction patterns synthesized from the experimentally obtained patterns shown in FIGURE 6. Three diffraction patterns 102, 104, 106 were synthesized by superimposing the patterns 100 of FIGURE 6 for monochromatic unmodulated signals properly weighted in accordance with the spectral characteristics of the modulation and the spectral filtering introduced by PMD. Employing the diffraction patterns 100 separated by 1.25 GHz will provide a fine enough resolution for accurate simulation, since, as discussed with reference to FIGURE 5, the shift of the diffraction pattern caused by the about 0.01 nm difference in wavelength, or about 1.25 GHz difference in frequency, equals about half the period of the fastest spatial variation in the detected pattern. The middle curve 102 in FIGURE 7 is the diffraction pattern obtained for unmodulated monochromatic light by setting the weights all equal. Accordingly, this curve 102 resembles an envelope over the plurality of curves 100 in FIGURE 6. This curve 102 represents the transfer function $h(x)$ for the diffractive array 68 over a 10 GHz bandwidth. The upper curve 104 in FIGURE 7 is the synthesized pattern for modulated light with no PMD, wherein the modulation corresponds to 10 GHz full wave half maximum (FWHM) Gaussian modulation. The fast spatial features seen on the middle curve 102 for the unmodulated signal become smeared out in the upper curve 104 as the modulation is turned on. This smearing effect is a result of the convolution of the optical power spectrum $S(x)$ of the modulated signal with the transfer function $h(x)$ of the diffractive array. The lower curve 106 in FIGURE 7 is the synthesized pattern for modulated light degraded by PMD, namely, 200 psec of differential group delay. The fast spatial features visible in the middle curve 102 return omewhat in the lower curve 106 as PMD filters the optical spectrum. Although the curve 106 represent the convolution of the optical power spectrum $S(x)$ of

the modulated signal with the transfer function *h(x)* of the diffractive array 68, the optical power spectrum is narrower as a result of PMD.

As described above, the fast Fourier transform is performed for each of the diffraction patterns. Diffraction patterns and corresponding Fourier transform distributions are produced as adjustments are made to the compensator 20, a ratio of the fast Fourier transform distributions being computed for two such adjustments to determine whether the adjustment improves or worsens the PMD. This process for compensating for PMD was simulated for an optical signal known to have 100 psec of differential group delay. Diffraction patterns were synthesized starting with the 100 psec of delay and for subsequent values in delay as would be achieved by adjusting the position of the mirror 62 in second arm 58 of the delay optics 46. Adjustments in delay at increments of plus and minus 20 psec were simulated. The fast Fourier transform of each diffraction pattern was performed and, as a figure of merit, the accumulated energy in the ratio of the consecutive distributions was computed. The results are listed in TABLE 1 below. Diffraction patterns for delays of 100, 120, and 80 psec were initially synthesized. Integrating over the ratio of fast Fourier transform distributions for 120 psec and 100 psec of delay yields 75.47 units, while for 80 psec and 100 psec of delay, the value is 61.01. With no change in delay, integrating over the ratio of fast Fourier transform distributions produces a value of 64 units. As described above, improvement in PMD compensation for this figure of merit occurs with a reduction in values. When the delay was reduced to 80 psec, the value obtained by integrating was decreased to below 64 units, the no-change reference. Accordingly, if the delay optics 46 was adjusted to reduce the delay by 20 psec to 80 psec, the figure of merit would indicate an improvement in PMD compensation. The remainder of TABLE 1 shows that selecting the direction of introduced delay that results in a value for the figure of merit that is lower than the no-change reference, which here is 64 units, will consistently lead to smaller amounts of differential delay.

TABLE 1

| 1st Delay Setting (psec) | 2nd Delay Setting (psec) | Ratio of Energy in FFT |
|---|---|---|
| 100 | 120 | 75.45 |
| | 80 | 61.01 |
| 80 | 100 | 88.44 |
| | 60 | 56.36 |
| 60 | 80 | 117.57 |
| | 40 | 48.62 |
| 40 | 60 | 92.31 |
| | 20 | 59.09 |
| 20 | 40 | 81.24 |
| 0 | 0 | 60.80 |

Thus, compensation for polarization mode dispersion of an optical signal propagating in an optical fiber 16 can be realized using a figure of merit based on the optical power spectrum and the autocorrelation function of an optical signal. This figure of merit is employed to impart delay in the fast component of the optical signal with the polarization mode dispersion compensator. A few inexpensive components can be used to implement this technique for compensating for polarization mode dispersion and the resultant implementation will be minimally affected by fluctuations in environmental conditions. This latter advantage accrues from using a figure of merit based on the ratio of the Fourier transform of the diffraction patterns. The transfer function *h(x)* of the tapped delay line diffractive array 68 is highly sensitive to environmental conditions like temperature. However, the term corresponding to the transfer function will drop out upon taking the ratio of the Fourier transform of the diffraction patterns. Thus, this figure of merit will not suffer from the sensitivity of the transfer function to environmental conditions, as long as *h(x)* does not change significantly over the time interval between successive readings.

In another embodiment of the present invention, a different figure of merit herein referred to as a flatness parameter is employed. The flatness parameter is a

measure of the relative flatness of the diffraction pattern, which indicates the level of PMD compensation that has been obtained. As discussed above, a signal after PMD compensation possesses an optical power spectrum that is clean and full. Convolving the transfer function $h(x)$ with an optical power spectrum $S(x)$ that is clean and full smoothens and flattens the resultant diffraction pattern. Accordingly, monitoring the relative flatness of the diffraction pattern enables a determination to be made as to when the optical power spectrum is clean an full and, thus, whether adjustments in the compensator 20 improve the PMD compensation. Diffraction patterns and corresponding flatness parameters are produced as the compensator 20 is adjusted. A ratio of the flatness parameter is computed for two such adjustments to ascertain whether the adjustment improves or worsens the PMD. Thus, instead of taking the ratio of the Fourier transform of the diffraction patterns, the ratio of the flatness parameters is computed.

The flatness, i.e., the amount of peaks and variations in the diffraction pattern, is characterized by the variance or standard deviation of the pattern. Accordingly, the flatness parameter preferably comprises the ratio of the standard deviation normalized to the mean or average value of the diffraction pattern at the optical detector. Alternatively, the flatness parameter may comprise the ratio of the variance to the mean. A smaller variance or standard deviation and, thus, a smaller value for the flatness parameter, indicates improvement in PMD compensation. This trend was verified for a series of experimentally obtained diffraction patterns produced by optical signals having 120, 100, 80, 60, 40, 20, and 0 psec of differential group delay. As a figure of merit, ratios of the flatness parameter for incremental changes in delay were calculated, the results of which are listed in TABLE 2. In particular, a ratio of the flatness parameter was computed for two amounts of delay; the value of this ratio indicates whether the amount of delay has increased or decreased. The ratios are less than one for reductions in delay, and are greater than one for increases in delay; however, this rule is subject to experimental error. With no change in delay, the flatness parameter is unity. More significantly, a smaller value for the ratio, i.e., figure of merit, results when the delay is reduced, which is consistent with PMD compensation. For example,

increasing the delay from 100 to 120 psec produces a ratio of 1.1483 units. In contrast, reducing the delay from 100 to 80 psec results in a lower ratio of 1.0605. Accordingly, if the delay optics 46 was adjusted to reduce the delay by 20 psec from 100 psec to 80 psec, the figure of merit would indicate an improvement in PMD compensation. The remainder of TABLE 2 shows how the consecutive reduction of delay in these signals, which could represent improvements in PMD due to compensation using the delay optics 46, correlate with reductions in values of the figure of merit.

TABLE 2

| 1st Delay Setting (psec) | 2nd Delay Setting (psec) | Ratio of Flatness Parameter |
|---|---|---|
| 100 | 120 | 1.1483 |
| | 80 | 1.0605 |
| 80 | 100 | 0.9430 |
| | 60 | 0.9298 |
| 60 | 80 | 1.0755 |
| | 40 | 1.0059 |
| 40 | 60 | 0.9941 |
| | 20 | 0.8587 |
| 20 | 40 | 1.1645 |
| 0 | 0 | 1.1044 |

The effectiveness of employing the ratio of autocorrelation functions or the ratio of flatness parameters as figures of merit presumes that digital data has a frequency spectrum that does not change and that the diffraction pattern for a monochromatic optical signal is therefore stationary. However, digital signals comprising statistically independent bits of data have an optical spectrum, and hence, a detected diffraction pattern, that can be considered stationary when averaged over a period of time. The assumption that the pattern is stationary is realistic since even one microsecond (μsec) integration time represents an average of over 10,000 bits for a data rate of 10 Gbits/sec.

Advantageously, the apparatus 10 and method of the present invention for compensating for polarization mode dispersion in an optical signal rely on optical processing of the optical signal to quantify the amount of PMD. In particular, an optical spectrum analyzer is employed to obtain information about the optical power spectrum of the optical signal. This spectrum analyzer produces an optical image, here a diffraction pattern, that contains spectral information. The intensity of this optical image is sampled at a plurality of locations across the optical image to retrieve data about the optical power spectrum of the signal. Characteristics of the optical power spectrum are then used to determine the amount of PMD. Specifically, in the case where the tapped delay line diffractive array is employed, the optical processing of the optical signal comprises interfering a plurality optical signals to create a spatial light distribution that is a diffraction pattern. The optical signals that are interfered are time delayed versions of the optical signal input into the apparatus 10; accordingly, the optical coherence of the optical signal is analyzed.

Relying on optical processing of the optical signal to quantify the amount of PMD in the signal provides numerous advantages over conventional PMD compensation schemes, which direct the optical pulses comprising the optical signal to the detector and then monitor the electronic pulses (or its frequency distribution) after the optical pulse has been transformed into an electrical pulse. In particular, a slower optical detector and detector circuitry can be employed in accordance with the present invention, i.e., the optical detector 30 need not be fast enough to detect the individual digital optical pulses and to generate an equally fast electrical pulse. Rather, the apparatus 10 integrates over a period of time much larger than the width of a single optical pulse. As discussed above, integrating over many bits of data is necessary to ensure that the diffraction pattern for a monochromatic optical signal is stationary. Since the optical detector 30 employed in the apparatus 10 for compensating for polarization mode dispersion need not be fast enough to discriminate between the optical pulses, the speed requirement for the detector 30 and detector electronics is relaxed and, accordingly, the expense of the optical signal sensor 22 is lowered. Also, because the apparatus 10 integrates over a period of time, less optical signal need be

coupled into the optical signal sensor 22 to satisfy the signal-to-noise requirements of the optical detector 30 and detector electronics. In contrast, in conventional systems, a substantial amount of optical signal must be detoured away from the receiver to overcome shot noise in the optical detector used to monitor the PMD. One additional advantage of the apparatus 10 for compensating for PMD is that the chromatic dispersion does not affect the diffraction pattern generated at the optical detector 30. More specifically, the diffraction pattern does not contain contributions from both chromatic dispersion and polarization mode dispersion. Accordingly, PMD can be compensated more precisely than can techniques that cannot distinguish between polarization mode dispersion and chromatic dispersion.

The specific arrangement of the delay optics 46 also offers advantages over other designs for compensating for delay caused by PMD. In particular, the number of beamsplitters 54 in the delay optics 46 is reduced to one, and the number of mirrors 62 are reduced to two. The reduced number of components means that initial alignment is simplified. Furthermore, only one of these mirrors 62 need be translated, and alignment is maintained even during translation. This arrangement is also compact.

The present invention may be embodied in other specific forms without departing from the essential characteristics as described herein. The embodiments described above are to be considered in all respects as illustrative only and not restrictive in any manner. The scope of any invention is, therefore, indicated by the following claims rather than the foregoing description. Any and all changes which come within the meaning and range of equivalency of the claims are to be considered in their scope.

What is Claimed is:

1. An apparatus for compensating for polarization mode dispersion of an optical signal propagating in an optical fiber, the apparatus comprising:

compensator optics having an input which receives the optical signal and an output which outputs the optical signal; and

an optical signal sensor which receives a portion of the signal output from the compensator optics and analyzes the polarization mode dispersion of the optical signal, the sensor providing a compensation signal to the compensation optics indicative of the amount of polarization mode dispersion, the compensator optics responsively altering the optical signal to compensate for the polarization mode dispersion, the optical signal sensor including an optical processor operatively associated therewith which generates a spatial pattern and a detector situated so as to measure an intensity at a plurality of locations across the spatial pattern, the optical signal sensor generating the compensation signal in response to the intensity measured.

2. The apparatus of claim 1 wherein the detector is a detector array.

3. A method for producing a compensation signal for driving compensator optics in a polarization mode dispersion compensation apparatus, the method comprising the steps of:

optically processing an output of the compensator optics to produce an optically processed signal having a spatial distribution;

directing the processed signal onto a detector;

measuring intensity at a plurality of locations across the spatial distribution to thereby produce an intermediate signal; and

processing the intermediate signal to generate the compensation signal.

4. The method of claim 3 wherein processing the intermediate signal comprises the step of:

performing a Fourier transform on the intermediate signal.

5. The method of claim 3 wherein the step of processing the intermediate signal further comprises the step of:

quantifying variation across the spatial distribution.

6. The method of claim 5 wherein the variation is quantified by computing a ratio of standard deviation to mean for the spatial distribution.

7. The method of claim 5 wherein the variation is quantified by computing a ratio of variance to mean for the spatial distribution.

8. An apparatus for compensating for polarization mode dispersion of a first optical signal corresponding to a train of optical digital data pulses propagating at a bit rate, *R*, in an optical fiber, the apparatus comprising:

compensator optics having an input which receives the first optical signal and an output which outputs the first optical signal; and

an optical signal sensor which receives a portion of the signal output from the compensator optics and analyzes the polarization mode dispersion of the optical signal, the sensor providing a compensation signal to the compensation optics indicative of the amount of polarization mode dispersion, the compensator optics responsively altering the first optical signal to compensate for the polarization mode dispersion, the optical signal sensor comprising an optical processor which generates a second optical signal including a signal other than a train of optical digital data pulses propagating at a bit rate *R*, the sensor generating the compensation signal in response to the second optical signal.

9. An apparatus for compensating for polarization mode dispersion of an optical signal propagating in an optical fiber, the apparatus comprising:

compensator optics having an input which receives the optical signal and an output which outputs the optical signal; and

an optical signal sensor which receives a portion of the signal output from the compensator optics and analyzes the polarization mode dispersion of the optical signal, the sensor providing a compensation signal to the compensation optics indicative of the amount of polarization mode dispersion, the compensator optics, responsively altering the optical signal to compensate for the polarization mode dispersion, the optical signal sensor including an optical processor which has a transfer function and which generates a spatial pattern corresponding to the convolution of the spectral distribution of the signal output from the compensator optics with the transfer function, the sensor generating the compensation signal in response to the spatial pattern.

10. The apparatus of claim 9 wherein the processor is a spectrum analyzer which includes a tapped delay line diffractive array.

11. The apparatus of claim 10 wherein the array is a plurality of optical fibers.

12. The apparatus of claim 9 wherein the processor is a plurality of waveguide devices.

13. A method for producing a compensation signal for driving compensator optics in a polarization mode dispersion compensation apparatus, the method comprising the steps of:

optically processing an output of the compensator optics to produce an optically processed signal using an optical device having a transfer function to produce a spatial distribution which corresponds to the convolution of

the spectrum of the output of the compensator optics with the transfer function;

directing the processed signal onto a detector to provide a detected signal; and

processing the detected signal to generate the compensation signal.

14. The method of claim 13 wherein the step of processing the detected signal comprises:

determining the Fourier transform of the detected signal.

15. The method of claim 13 wherein the step of processing the detected signal comprises:

quantifying a variation in intensity across at least a portion of the spatial distribution.

16. An apparatus for compensating for polarization mode dispersion of a first optical signal comprising optical pulses propagating in an optical fiber, the apparatus comprising:

compensator optics having an input which receives the first optical signal and an output which outputs the first optical signal; and

an optical signal sensor which receives a portion of the signal output from the compensator optics and analyzes the polarization mode dispersion of the optical signal, the sensor providing a compensation signal to the compensation optics indicative of the amount of polarization mode dispersion, the compensator optics responsively altering the first optical signal to compensate for the polarization mode dispersion, the optical signal sensor including an optical processor which generates a second optical signal and an optical detector having an integration time that is substantially longer than the time between adjacent optical pulses in the first optical signal, the detector receiving the second optical signal and

generating an electrical signal, the sensor generating the compensation signal in response to the electrical signal.

17. An apparatus for compensating for polarization mode dispersion of an optical signal propagating in an optical fiber, the apparatus comprising:

compensator optics having an input which receives the optical signal and an output which outputs the optical signal; and

an optical signal sensor which receives a portion of the signal output from the compensator optics and analyzes the polarization mode dispersion of the optical signal, the sensor providing a compensation signal to the compensation optics indicative of the amount of polarization mode dispersion, the compensator optics, responsively altering the optical signal to compensate for the polarization mode dispersion, the optical signal sensor including an optical processor which has a beamsplitter that splits the optical signal into a plurality of signals and a region where the plurality of signals optically interfere with each other to form an other optical signal, the sensor generating the compensation signal in response to the other optical signal.

18. A method for producing a compensation signal for driving compensator optics in a polarization mode dispersion compensation apparatus, the method comprising the steps of:

processing an output of the compensator optics to produce a processed signal, the processing including autocorrelating the processed signal at a time $t_1$ and a time $t_2$;

comparing the autocorrelation at time $t_1$ with the autocorrelation at time $t_2$; and

producing the compensation signal in response to the comparison.

19. The method of claim 18 wherein the step of comparing comprises:

comparing the ratio of the autocorrelations.

20. A method of controlling compensator optics in a polarization mode dispersion compensation apparatus comprising a polarization transformer and delay optics, the method comprising the steps of:

processing an input signal including an output of the compensator optics, the step of processing providing an optimization parameter;

measuring the optimization parameter; and

producing control signals for controlling both the polarization transformer and the delay optics in response to measurements of the optimization parameter.

21. The method of claim 20 wherein the optimization parameter is the ratio of an autocorrelation signal at a first time to the autocorrelation signal at a second time.

22. The method of claim 20 further comprising the step of:

altering the input signal to provide different measurements of the optimization parameter for controlling the delay and the polarization transformer.

23. An apparatus comprising:

compensator optics including a polarization transformer and delay optics, the compensator optics having an input for receiving light from an optical fiber which propagates light in first and second polarizations, the polarization transformer receiving light from the optical fiber, the delay optics receiving light from the polarization transformer and propagating light in third and fourth polarizations; and

an optical signal sensor which receives light from the compensator optics, the sensor comprising an optical element having first and second states, one of the states passing light of the third polarization while blocking light of the fourth polarization and the other of the states passing at least a portion of light of both the third and fourth polarizations, the sensor producing control signals for the polarization transformer when the

optical element is in the first state and producing control signals for the delay optics when the optical element is in the second state.

24. The apparatus of claim 23 wherein the optical element passes approximately equal portions of light of both the third polarization and the fourth polarization when in one of the states.

25. An apparatus for acting on beam of light, the apparatus comprising:
a polarization transformer;
delay optics, the delay optics including:
a polarizing beamsplitter for splitting the beam into a first beam and a second beam of different polarizations;
a mirror positioned to receive the first beam and reflect the first beam back to the polarizing beamsplitter;
a mirror positioned to receive the second beam and reflect the second beam back to the polarizing beamsplitter;
a first quarter-wave plate positioned in the path of the first beam; and
a second quarter-wave plate positioned in the path of the second beam;
the polarizing beamsplitter combining the reflected first beam and the second beam to provide an output beam; and
sensor optics.

26. The apparatus of claim 25 wherein the second mirror is mounted on an electronically controlled translation stage.

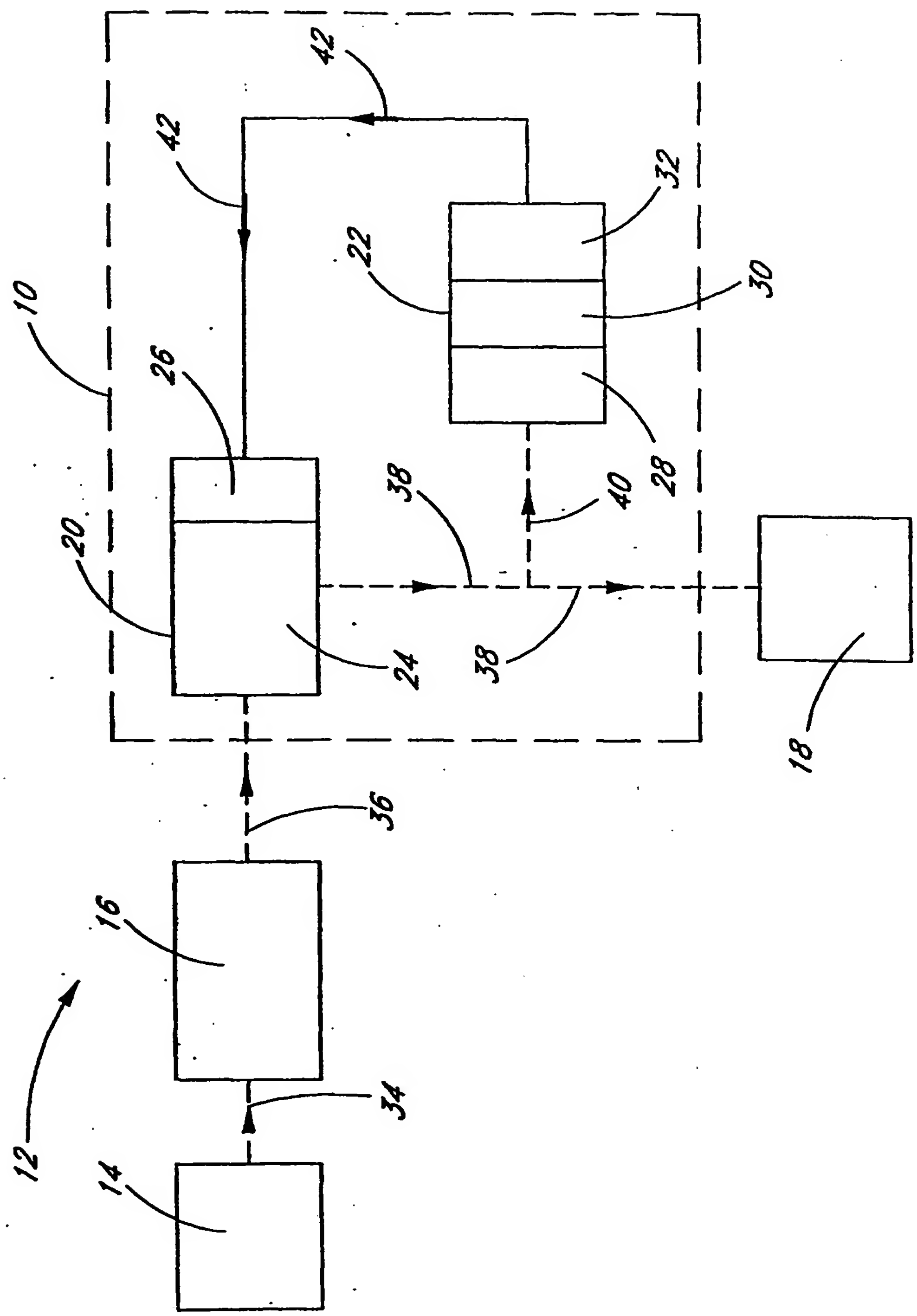


FIG. 1

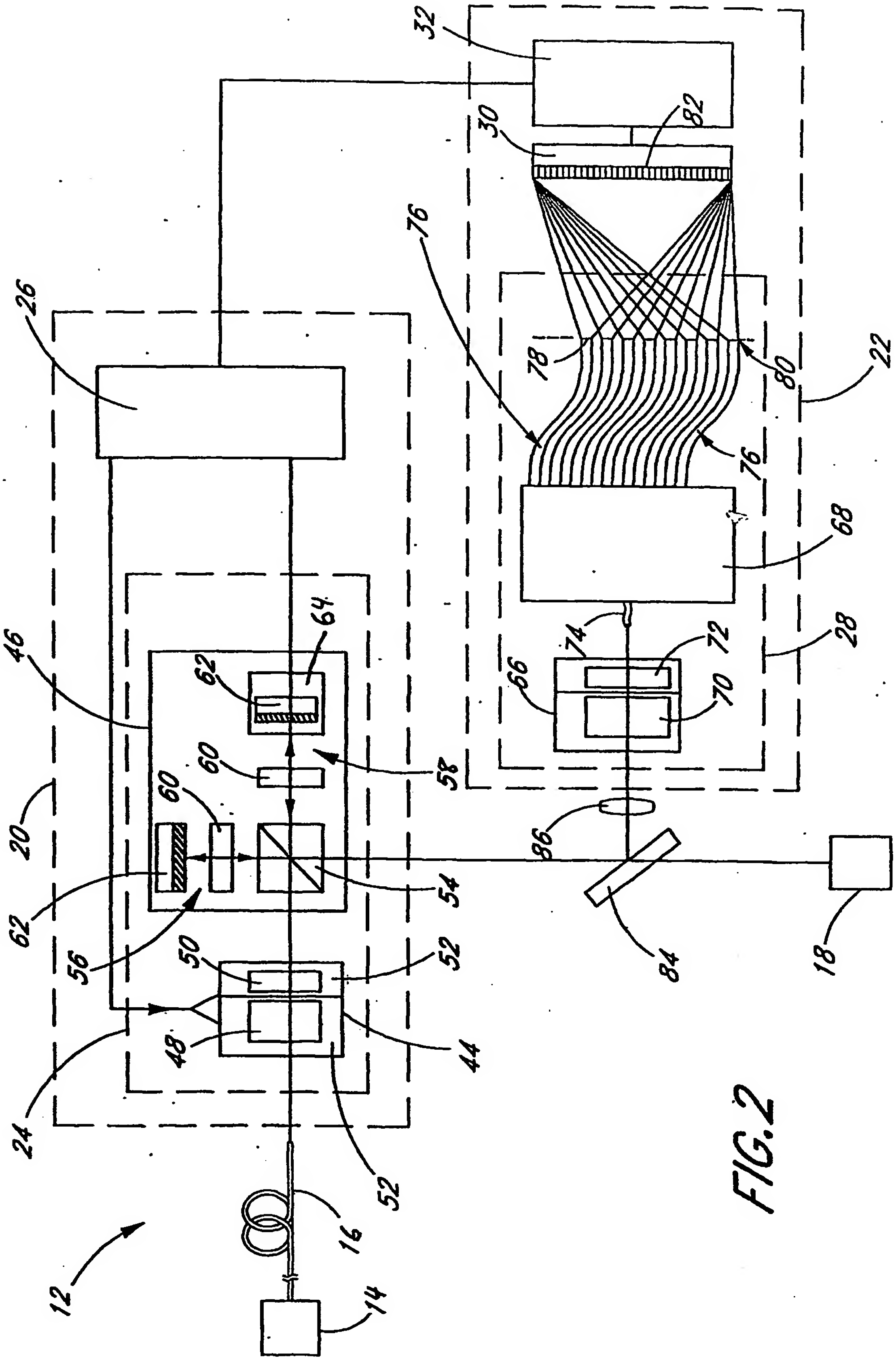
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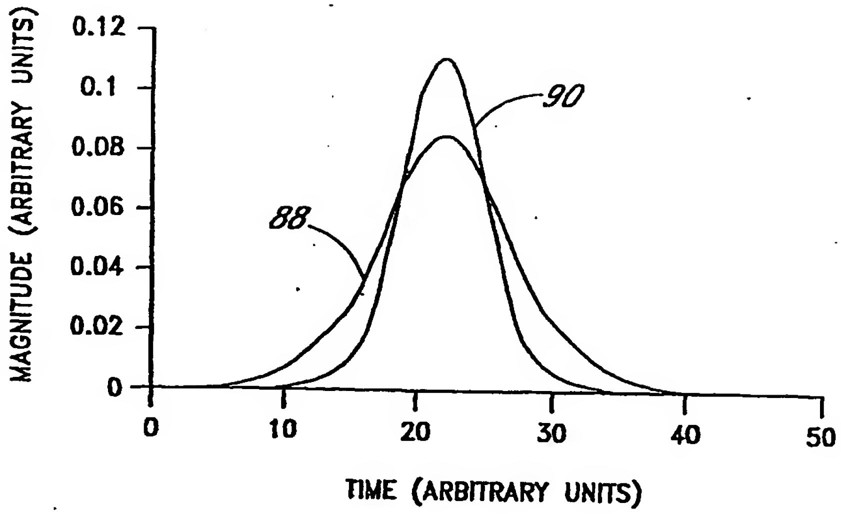
FIG.2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TIME (ARBITRARY UNITS)
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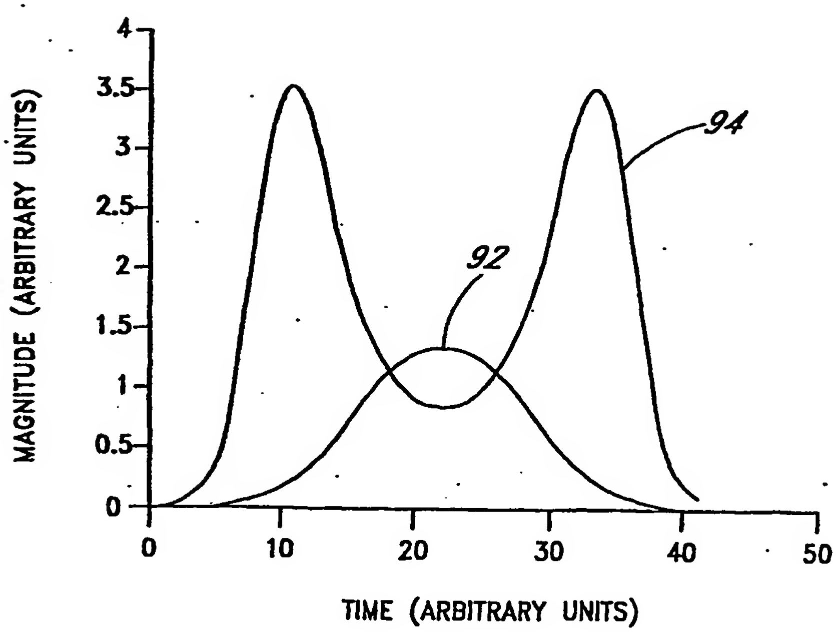
88

FIG. 3A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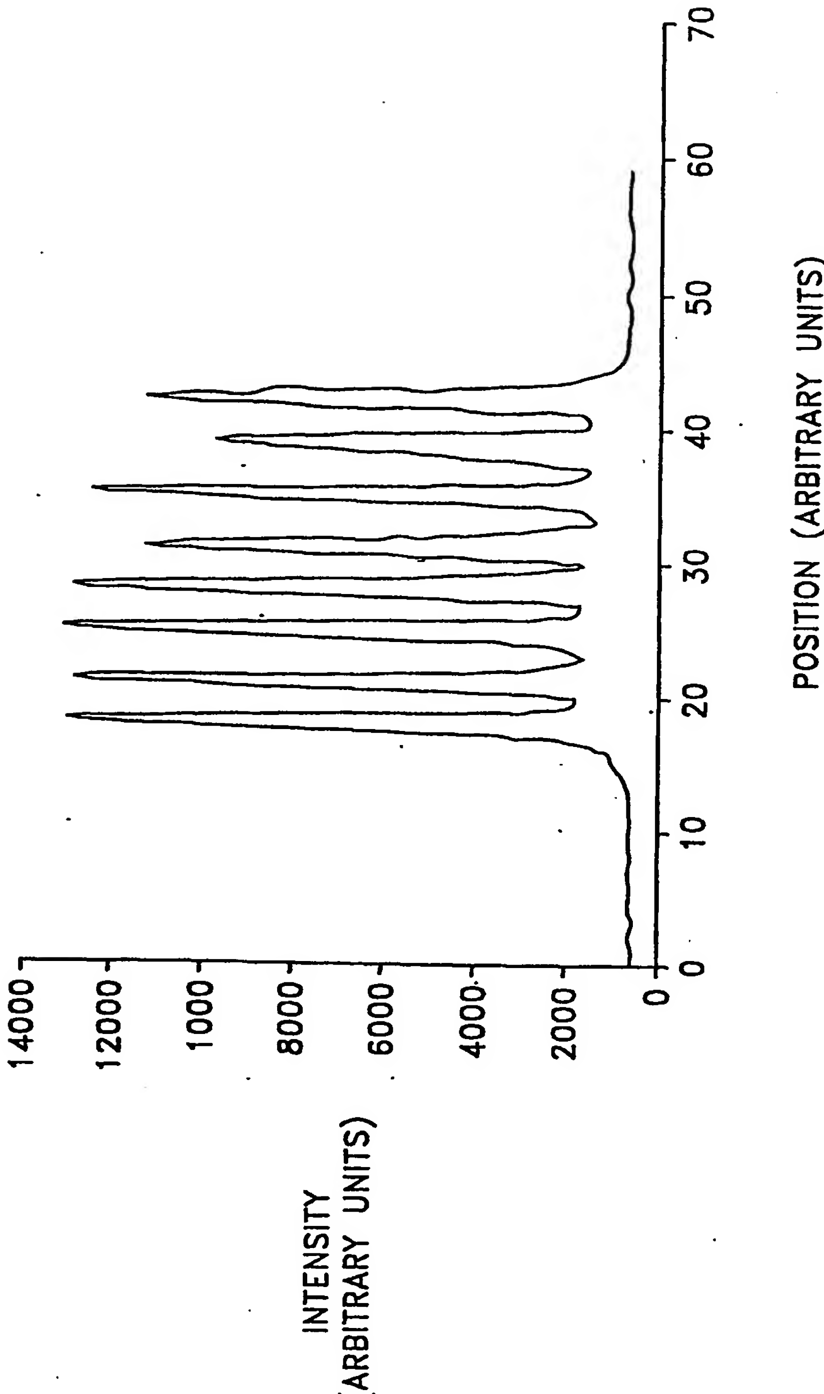
92

FIG. 3B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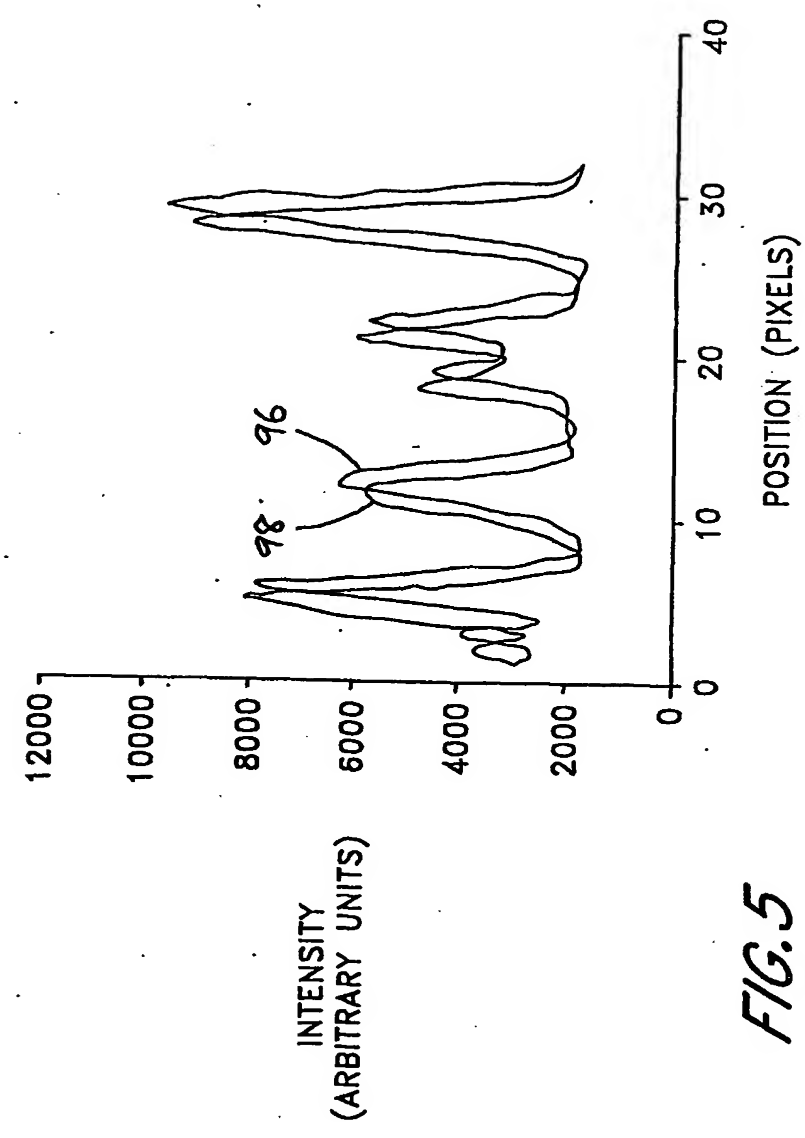
POSITION (ARBITRARY UNITS)

FIG. 4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POSITION (PIXELS)
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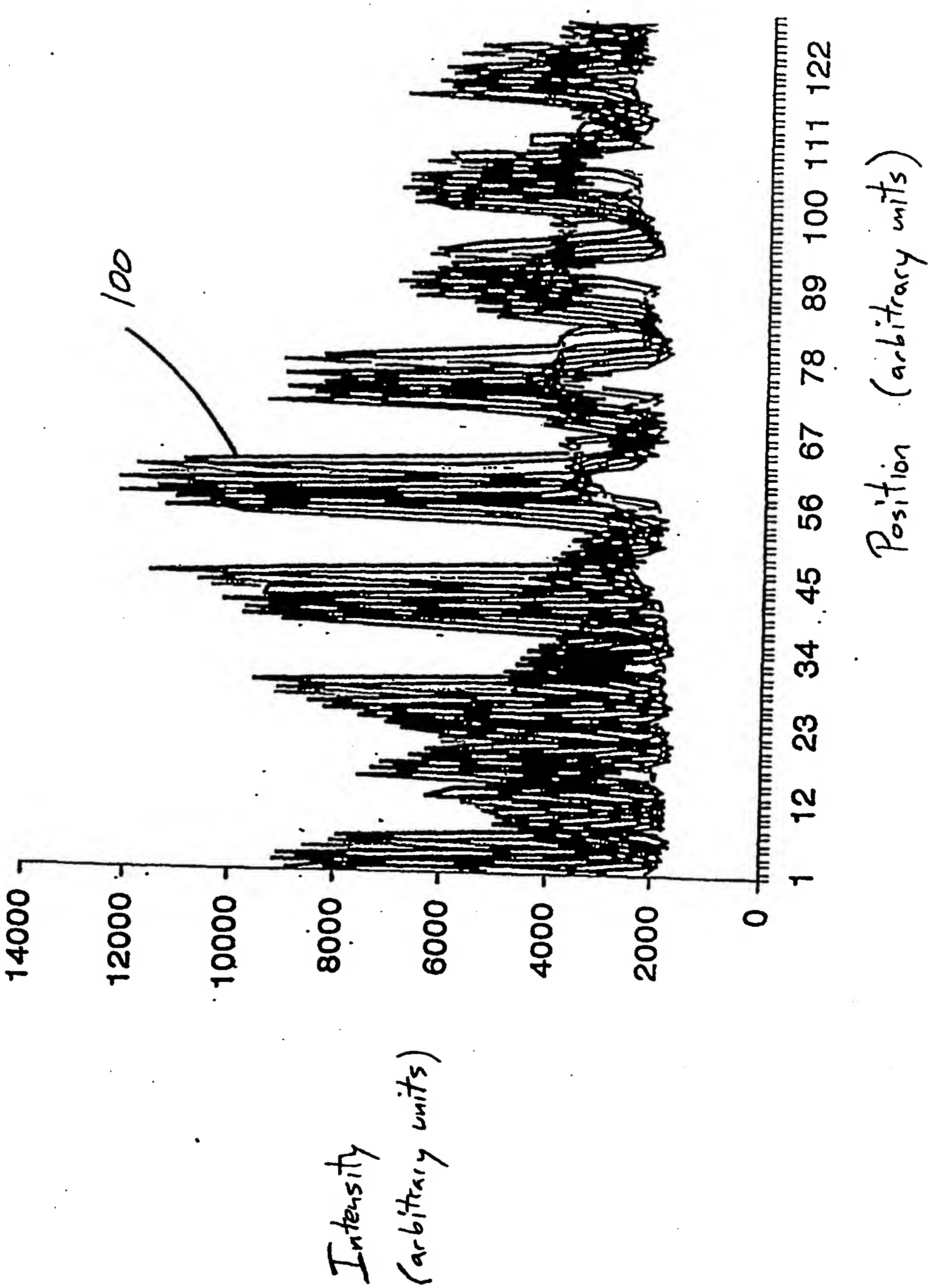
98

FIG.5

FIG. 6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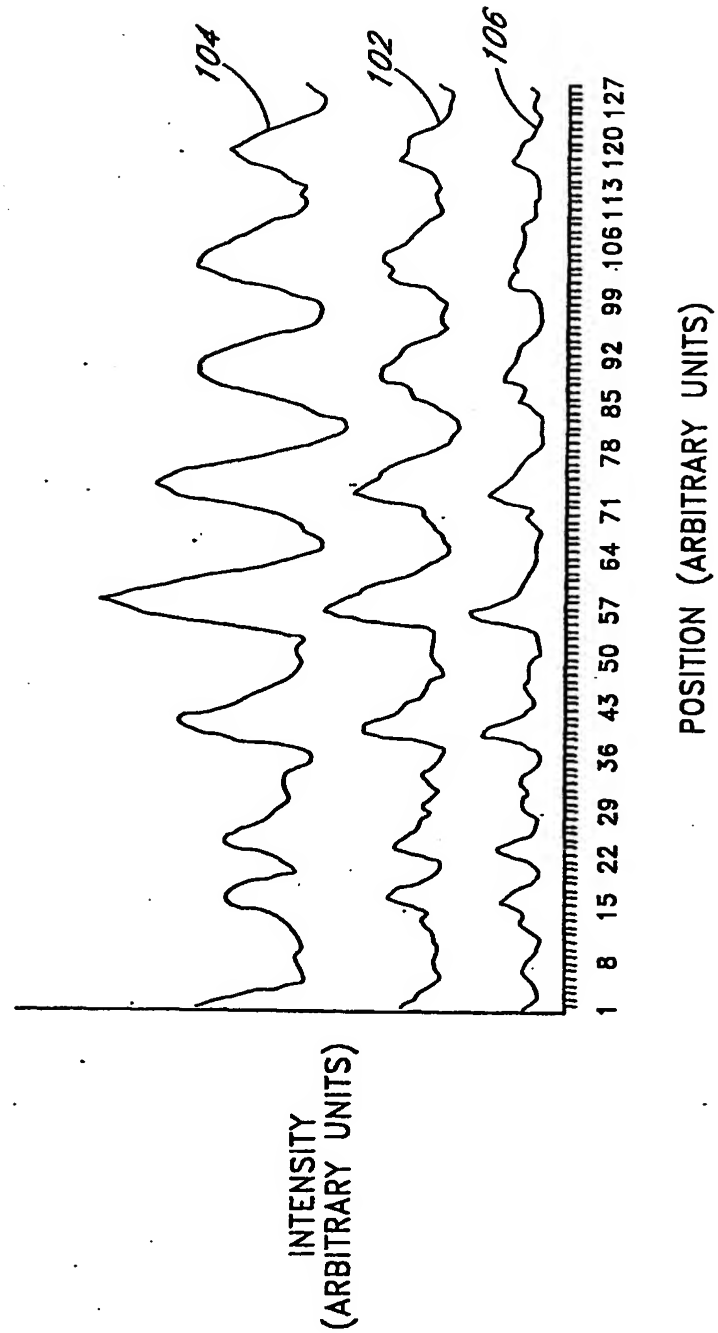
100
111
122
Position (arbitrary units)


104
102
106
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POSITION (ARBITRARY UNITS)
INTENSITY (ARBITRARY UNITS)

FIG. 7

# INTERNATIONAL SEARCH REPORT

International application No.
PCT/US01/08691

**A. CLASSIFICATION OF SUBJECT MATTER**

IPC(7) : H04B 10/06
US CL : 359/192

According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)
U.S. : 359/192, 156

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

| Category * | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| Y, E | US 6,208,444 B1 (WONG et al.) 27 March 2001 (27.03.2001), entire document. | 1-8, 17-26 |
| Y, P | US 6,178,021 B1 (BRUYERE et al.) 23 January 2001 (23.01.2001), entire document. | 1-8 |
| Y, P | US 6,163,393 A (WU et al.) 19 December 2000 (19.12.2000), entire document. | 1-8, 17-26 |
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